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Two-dimensional photonic crystals for GaN-based blue light emitters

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Abstract
We successfully fabricated two-dimensional photonic crystal structures for III-nitride light emitters by integrating electron-beam lithography, xenon/chlorine-based chemically assisted ion beam etching and a multilayer pattern transfer.

Introduction

Photonic crystals have recently attracted much attention because they can be used to control spontaneous emission in a small optical cavity[1,2]. By incorporating a defect in a photonic crystal, a high Q microresonator can be constructed. Low operating power and/or high modulation speed are expected from microcavity light emitters such as laser diodes (LDs) and light emitting diodes (LEDs) [3]. The high contrast of refractive index between semiconductors and air can produce photonic crystals in which light is efficiently reflected regardless a propagation direction. Though photonic crystal structure has been precisely fabricated in the long-wavelength compound semiconductor systems such as GaInAsP/InP and AlGaAs/GaAs [4], crystals for the blue regime have not been fabricated because of the difficulty associated with finer pattern-transfer. Recently, the performance of GaN laser diodes has drastically progressed. Laser lifetime is reported to exceed 1000 hours with cw room temperature operation[4]. However, GaN-based microcavity lasers and vertical cavity surface emitting lasers[5] have so far not been successfully realized. To approach these devices, we report techniques to fabricate 2D-photonic crystals for blue III-nitride light emitters, which are expected to realize in-plane tight optical confinement of light in GaN-based light emitters.

Fabrication and Results

Undoped GaN was used for this work. It was grown on c-face sapphire by metal organic vapor phase epitaxy (MOVPE). The total thickness of GaN epilayer is 2μm. The epilayers were confirmed to have good optical quality by low temperature photoluminescence measurement.

To transfer patterns into GaN, we developed multilayer pattern transfer. We used high-resolution electron beam lithography for patterning 2D-photonic crystal structures. Our 30kV electron beam writing system has a field emission filament and a nominal spot size of 1nm. Polymethylmethacrylate (PMMA) was used as a positive electron beam resist. This allows us to define fine patterns such as photonic crystals for GaN. As a mask, we deposited Au/Ni on top of a 300nm SiO_2 deposition on the GaN epilayer. After electron beam lithography on PMMA, patterns were transferred into the Au/Ni layer by argon ion milling and then into a SiO_2 layer by C_2F_6 reactive ion etching. Pattern-transfer into the GaN layer was conducted by Cl_2-based chemically assisted ion beam etching (CAIBE). Xenon was used as a sputtering ion beam instead of argon to enhance the etching rate. GaN was etched at 220°C while locally supplying Cl_2 in order to get vertical and smooth sidewall inside the etched trenches. The etching rate was 0.6μm/min. Our etching mask enables us to etch 1.5μm deep trenches. This is deep enough to confine light in-plane in active layers of InGaN/GaN/AlGaN LDs and LEDs. In InGaAs/GaAs microcavity LDs, trenches entering into the cladding layer under an active layer are deep enough to get a high Q in photonic crystal microcavity[6].

Before fabricating the structures consisting of triangular lattice of circular trenches, we calculated 2D-photonic band structure of the infinitely periodical triangular lattice by using the plane-wave expansion method [7]. The photonic bandgap is between 0.35 and 0.50 of normalized frequency when the modal refractive index is 2.72 and the ratio of trench radius to trench pitch, r/a, is 0.4. When we assume 410nm as the emission wavelength, suitable pitch of trenches ranges between 140 and 200nm in order that emission wavelength is in the photonic bandgap. Figure 1 shows scanning electron microscopy (SEM) images of photonic crystals with a range of different pitches.

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Fig.1(a),(b) and (c) have pitches of trench: 150, 170 and 190nm, respectively. A defect can be seen in photonic crystals in each image of Fig.1. The etched depth was confirmed to be over 1μm.

The tequnique described here can be easily applied to InGaN/GaN/AlGaN LDs and LEDs. In the InGaAs/InGaAsP system, a membrane structure is appropriate because of the high refractive index of the InP substrate. In GaN-based light emitters, however, we can use sapphire substrate whose refractive index is 1.77. Emission from the active region could be strongly localized in the defect when the 2D photonic crystal is applied to waveguide of the light in addition to such a vertically optical confinement structures.

Conclusion

We have demonstrated that 2D-photonic crystals for gallium nitride can be fabricated. The structures are enabled by integrating techniques of high resolution electron-beam lithography, Cl_2-based CAIBE with xenon ions and a multilayer pattern transfer.

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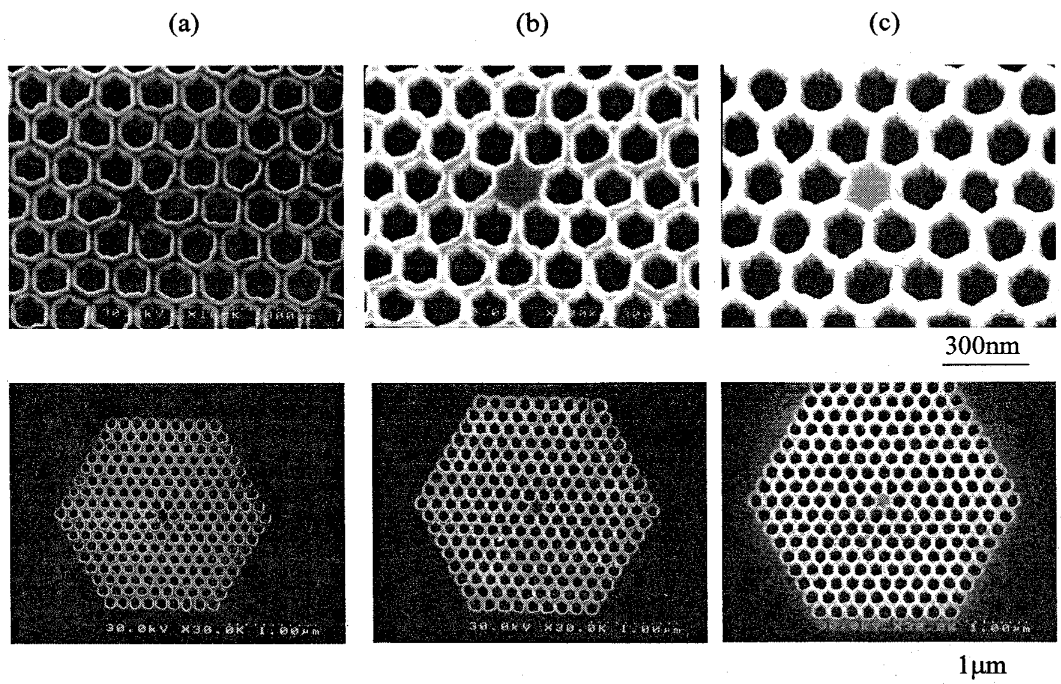

Fig.1 SEM images of photonic crystal structures consisting of triangular lattice in gallium nitride. Pitches of trench are (a)150, (b)170 and (c)190nm, respectively.